Full-Duplex Power Line Communications: Design and Applications from Multimedia to Smart Grid

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***Abstract*—Power line communication (PLC) superimposes high-frequency data signals ranging from a few hundred Hertz to hundreds of megahertz over the low-frequency electrical power carriers to reuse the existing power lines for communication purposes. Across various indoor and outdoor PLC application scenarios, the electromagnetic compatibility restrictions and the low-pass nature of power line channels restrict the data rate gains that can be furthered by conventional means of increasing power and/or bandwidth. In this article, we provide an overview of in-band full-duplex (IBFD) operation as a means to improve PLC under these constraints, by potentially doubling the spectral efficiency through simultaneous signal transmission and reception in the same frequency band and over the same power line. We summarize the recent advancements in IBFD solutions for both narrowband and broadband PLC and contrast the design considerations to those in existing IBFD methods in other communications systems. We also highlight the benefits of IBFD operation to PLC networks in easing PLC network congestion, ensuring electromagnetic compatibility of PLC across application scenarios, and obtaining added insights in the context of smart-grid monitoring and security using simultaneous bidirectional communication.**

I. INTRODUCTION

Data transfer over existing power lines has enabled power line communication (PLC) to find widespread applicability at all avenues where communication is required and electrical wires are available in some form. For example, PLC is applied for smart grid communication from consumer-end home area networks to transmission and distribution networks, for enabling the local area network and for home automation using the indoor wiring infrastructure, in in-vehicle and vehicle-to-infrastructure systems, and also in next generation battery management systems [1, Ch. 7–10]. Current-day PLC modems used in any of these application scenarios are typically half-duplex (HD) in nature, and employ time division duplexing (TDD) to separate the upstream and downstream data. In-band full-duplex (IBFD) transmission is a technology that does not require the time or frequency separation of upstream and downstream data, and thus, it can offer a potential doubling of bidirectional throughput for a given channel quality. While the ability to double data rates without any additional power or bandwidth requirement is appealing for all types of communication systems, it is even more attractive for PLC due to (i) the strict transmit power spectral density (PSD) restrictions imposed by regulatory authorities to limit unintentional electromagnetic radiations [1, Ch. 3], and (ii) the low-pass nature of power lines, which severely limits the achievable spectral efficiencies for higher frequencies [1, Ch. 2].

A fundamental impediment for successful IBFD implementation is the large interference caused by the transmitted signal. Due to simultaneous bidirectional communication, the received signal consists of a superposition of the signal-of-interest (SOI), noise, and the portion of the transmitted signal interfering with the SOI, which is referred to as self-interference (SI) or echo. Depending on the power line channel attenuation, the echo can be a few hundred to several billion times stronger than the SOI, resulting in a poor signal-to-self-interference-plus-noise ratio (SSINR) at the receiver.

The communication environment can be improved by using one or more SI reduction methods to increase the SSINR. Since IBFD is not a new technique and has been used since the 1940s in radio detection and ranging (RADAR), analog telephones, digital subscriber line (DSL), Ethernet, coaxial cable communications, and also more recently in wireless communications, there is a plethora of SI and echo cancellation techniques available in the literature [2]. The need to *re-invent* IBFD solutions for each communication system arises from the specific challenges introduced by the communication medium, hardware constraints within the device, and the operating signal power levels. In this article, we provide an overview of the unique challenges encountered in power line channels that render a direct adoption of the SI reduction method(s) from other IBFD systems ineffective for PLC. At the same time, baseband transmission used for PLC also provides the opportunity to simplify the IBFD design, as it eliminates the necessity of handling analog imperfections associated with transmission in radio-frequencies (RF).

The IBFD operation is known to benefit communication systems beyond potentially doubling data rates. Examples include improving the relaying efficiency in multihop networks, solving the hidden-node problem without a dedicated handshake protocol, and providing implicit physical layer security in bidirectional point-to-point communication [2]. While these enhancements are observable in any communication system, novel adaptations of the IBFD operation assist in designing efficient countermeasures to specific challenges faced in present-day PLC deployments. In the latter half of this article, we summarize key advancements that have been achieved in solving electromagnetic compatibility and power line networking issues in PLC deployments using IBFD-based solutions. Finally, we highlight a lateral benefit of the IBFD operation, where simultaneous transmission and reception can be exploited for grid diagnostics when PLC is used for smart

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grid communications. Considering this progress, IBFD for PLC has been proposed as a study-item to be incorporated into the upcoming G.hn2 standard for unified wire-line communications for home networking [3]. In this article, we detail all the above aspects of IBFD-PLC, beginning with the basics of the SI reduction method necessary for achieving simultaneous in-band bidirectional communication.

II. SI REDUCTION

SI reduction techniques can be broadly classified into two categories, namely, echo suppression and interference cancellation. Echo suppression involves attempting to isolate the transmitted signal from the incoming SOI so that the composite received signal is corrupted by minimal SI. On the other hand, interference cancellation actively uses the known transmitted signal to recreate the echo to remove it from the received signal. For most IBFD communication systems, a combination of one or more echo suppression and interference cancellation methods is required to achieve the necessary SI reduction. For example, IBFD Wi-Fi systems, which require a total SI reduction of over 110 dB, typically reduce the SI in three successive stages [2]. In contrast, PLC operates in a much harsher noise environment, where ~ 80 dB reduction in the transmit signal level is sufficient to scale its impact down to that of the power line noise floor [4]. In this section, we summarize the key design considerations for an IBFD-PLC solution to meet the target SI reduction for both narrowband (NB) and broadband (BB) PLC, by highlighting and distinguishing the challenges faced in each of them.

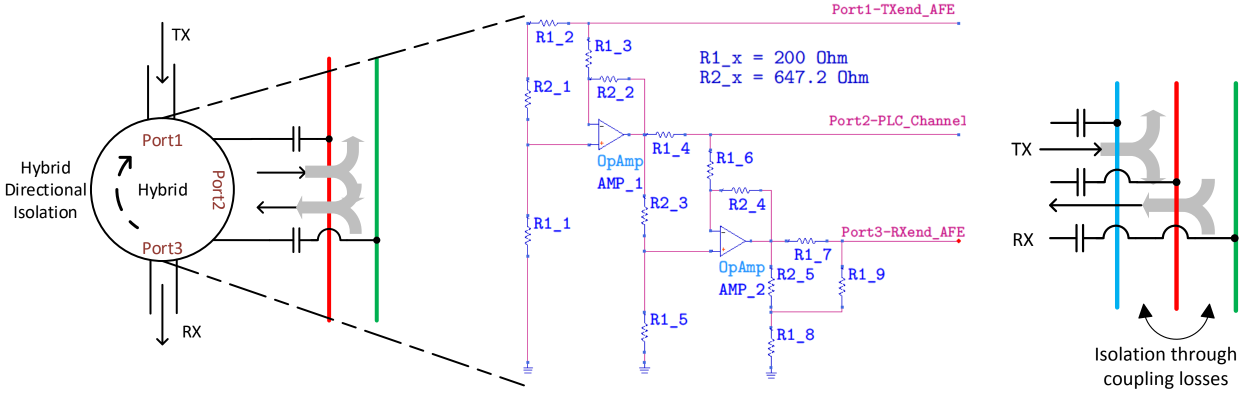
A. *Echo Suppression*

The type of echo suppression to be chosen is dependent on the front-end architecture of the device. For example, a unidirectional circulator, which ideally isolates the bidirectional signals from each other, is suitable for IBFD wireless communication user equipments that have a single transmitter (Tx) and receiver (Rx) antenna. Whereas, devices that use two separate antennas for Tx and Rx, typically choose from one of antenna spacing/separation/isolation techniques to reduce the amount of the Tx signal interfering with the SOI [2]. However, this flexibility is often absent in the scenario of wired communications, where the Tx and Rx signals are commonly fed into and out of the same conductor(s). Therefore, a single-antenna type solution seems applicable for IBFD wire-line systems.

Ferrite circulators that are proposed to provide isolation in single-antenna wireless communication devices operating in the lower gigahertz frequency range are unsuitable for most wire-line systems that transmit signals at less than a few hundred megahertz. At these frequencies, the size of the ferrite circulator required is prohibitive [5]. Hence, using an active operational amplifier (op-amp) based three-port hybrid circuit [5], which is also referred to in the literature as 4-to-2 transformer, is a practical approach for achieving echo suppression. The use of such a hybrid with active op-amp elements serves a second purpose for PLC. Typical PLC modems use a low impedance Tx path and a higher impedance Rx path in the analog front-end for efficient HD operation [1, Ch. 4]. When both these paths are simultaneously activated in the IBFD mode, the effective input impedance of the modem is substantially reduced, which leads to significant attenuation of the SOI. With the use of an op-amp based hybrid, such as the one shown in Fig. 1(a), its port impedances connected to the Tx path, power line, and the Rx path can be independently customized to ensure that the SOI strength is maintained at the same level as that seen in the HD mode [4].

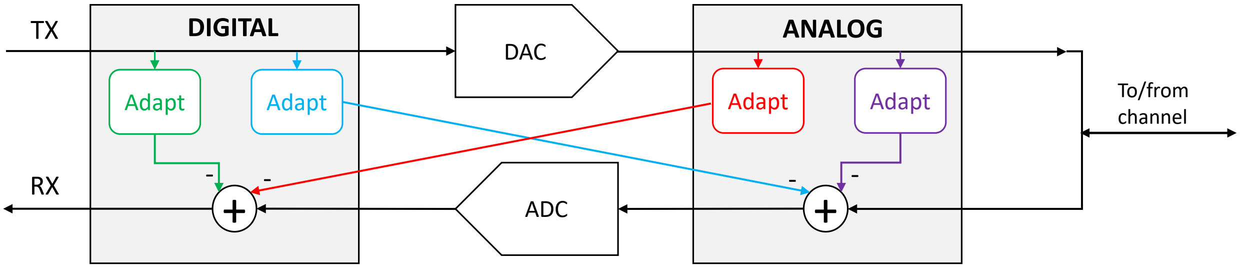
Wire-line systems that have multiple conductors at their disposal, such as PLC applied in a multi-phase distribution infrastructure or in indoor networks with line-neutral-ground wiring, can also optionally employ a multi-antenna-type echo suppression. Although wire-line systems do not enjoy the flexibility of placing *antennas* at will, such as in wireless scenarios for antenna spacing or separation, the existing wire configuration can be exploited to achieve initial signal isolation. Fig. 1(a) and (b) show the coupling of power line signals on a single conductor pair and multiple wires, respectively. In the case of using a single pair of conductors for single-input single-output (SISO) PLC, isolation is provided using the hybrid circuit, as discussed before. However, for multi-conductor PLC, echo suppression can be achieved using the coupling losses between the different paths, with one pair of conductors used for transmission and another for reception. While this approach does not require the additional hybrid component, it, however, has an evident drawback that it uses double the resources (wire-pairs) for SISO operation that can alternatively be used for multiple-input multiple-output (MIMO) communications. On the other hand, a hybrid-based isolation technique provides the ability to use all available conductors for MIMO IBFD communication with each wire-pair used for bidirectional PLC. Therefore, although *multi-antenna* isolation via coupling losses between different conductor paths is feasible, the *single-antenna* architecture with hybrid-based echo suppression is more suitable for PLC, and likewise for other wired communication systems.

If the hybrid completely provides the desired SI reduction, no further interference cancellation is required within the IBFD modem. However, echo suppression achieved in PLC is often far from ideal. Although the hybrid removes nearly all of the leakage signal, the primary source of residual SI is the Tx signal component reflected from the line [4]. Therefore, the isolation obtained is dependent on the extent of impedance mismatch at the hybrid port and power line interface. Since the access impedance is unknown and widely varying, achieving impedance matching is challenging. Although a recent study showed that dynamically adapting the hybrid port impedance to reduce the impedance mismatch can produce greater SI isolation compared to a fixed impedance architecture [6], the echo suppression this design provides is still far from sufficient to solely meet the total SI reduction target of 80 dB for IBFD PLC. Therefore, interference cancellation is required to be further implemented inside the IBFD modem to achieve satisfactory SI reduction.



(a) (b)

Fig. 1. Two options for achieving echo suppression in PLC, where (a) transmission and reception paths are coupled onto the same conductor pair, where the image also shows the zoomed-in circuit diagram of the op-amp based hybrid used, or (b) onto different conductor pairs. The hybrid port impedances in (a) are tuned to 100 Ω in an attempt to match the typical access impedance at Port 2 connected to the line, and to bridge and match impedances at Port 1 and Port 3 connected to the Tx and Rx chains of the analog front-end, respectively.



Critical for RF, but possibly benign for baseband transmission, such as PLC

Mandatory, if required cancellation is greater than ADC range, as typically the case for BB-PLC

Factors of consideration	**D – DIC**	**D – AIC**	**A – DIC**	**A – AIC**
Capture analog imperfections	×	×	✓	✓
Counter ADC dynamic range limitation	×	✓	×	✓
Adapt efficiently under rapidly varying SI channels	✓	✓	×	×
Require no additional hardware modifications	✓	×	×	×

Fig. 2. The choice of interference cancellation types depending on the requirements of the communication system.

B. Interference Cancellation

Interference cancellation involves using the known Tx signal, either in the digital or analog form, to replicate the echo interfering with the SOI, so that it can be removed from the composite Rx signal. Subtracting the replicated echo from the Rx signal can also be performed either in the analog or digital domain. Fig. 2 shows various usable interference cancellation configurations. Across configurations, the tapped Tx signal is passed through an adaptation module, which is typically a finite impulse response (FIR) filter that emulates the SI channel, to replicate the echo. Depending on the domain in which the Tx signal is tapped, adapted, and canceled, interference cancellation methods can be roughly categorized into four classes, namely, digitally controlled digital interference cancellation (D-DIC), digitally controlled analog interference cancellation (D-AIC), analog controlled digital interference cancellation (A-DIC), and analog controlled analog interference cancellation (A-AIC), as illustrated in Fig. 2.

Each of these techniques have their own costs and benefits. Tapping the Tx signal as far into the analog Tx chain as possible enables us to capture the distortion effects introduced by various components in the analog front-end. Such distortions are pronounced in RF wireless communications due to the presence of up- and down-converters that introduce phase noise and cause in-phase/quadrature imbalance in the Tx-Rx chain. Therefore, interference cancellation methods that tap signals in the analog domain are known to provide greater overall SI reduction in IBFD wireless solutions [2]. The drawback with tapping and adapting signals in the analog domain is the complexity involved in adapting the analog FIR filter weights continually to rapidly varying channel conditions, which are commonly seen in PLC where considerable channel changes are noticeable within 700 μs. On the other hand, D-xIC, which allows for tapping the Tx signal and filtering it digitally, provides higher performance efficiency under rapidly changing channel conditions. Since baseband communication, as used in PLC and many other wire-line systems, does not use mixers in the Tx/Rx chain, D-xIC together with modest echo suppression often suffice to provide adequate SI reduction. Nevertheless, choosing the domain in which signal subtraction is performed requires further scrutiny.

When the emulated echo is removed digitally, i.e., for x-DIC methods, the limiting factor for the maximum achievable interference cancellation is the dynamic range of the analog-to-digital converter (ADC). A sufficient ADC resolution that introduces a quantization noise lower than the pre-ADC noise floor ensures that x-DIC achieves sufficient interference cancellation that can provide an SSINR in IBFD mode to be nearly the same as the signal-to-noise ratio (SNR) achieved by the HD operation under the same communication conditions. This guarantees a true doubling of bidirectional transfer rates under any channel and noise condition. Alternatively, certain IBFD systems can afford to tolerate SSINR degradation without compromising on the IBFD performance, due to its operating channel condition. For example, NB-PLC can achieve satisfactory IBFD performance despite the potential impact of quantization noise as it operates in the lower kilohertz frequency range, where power line channel attenuation is typically much smaller than that seen by BB-PLC systems. Thus, a degradation in an already high SSINR may not cause a noticeable difference in the practical data rates. Hence, since an all-digital interference cancellation requires no additional hardware modifications and also provides adequate SI reduction, D-DIC may be sufficient for NB-PLC [7, Sec. 3.5.6], [8]. On the other hand, the SOI in BB-PLC could be up to a billion times weaker than the Tx signal. Therefore, degradation of SSINR due to SI quantization noise has noticeable impact on the bidirectional data rates [4]. For such systems, D-AIC, which captures the benefits of efficient digital SI adaptation and analog signal removal ensures that the limited dynamic range of practical ADCs does not restrict the achievable SI reduction [9].

Digital SI estimation for both NB- and BB-PLC IBFD solutions use an adaptive estimation algorithm to accommodate the changing PLC channel conditions. However, while NB-PLC, which operates in the frequency range of less than 500 kHz can estimate the SI channel impulse response with relatively low computational complexity, a time-domain echo channel estimation over large bandwidths of up to 100 MHz used by BB-PLC is computationally intensive. Instead, since most BB-PLC systems use orthogonal frequency division multiplexing (OFDM) for transmission, it is preferable to estimate the SI channel frequency response using a one-tap-per-sub-carrier FIR filter [4]. With channel estimation performed digitally in both the time- and frequency-domain methods, adaptive algorithms can be efficiently implemented for obtaining accurate estimates. The least mean squares (LMS) adaptive estimation algorithm is commonly used in most system identification problems as it provides the optimal performance after convergence. However, conventional LMS implementation for IBFD-PLC requires a compromise on its performance to use a larger adaptation step-size to accommodate the rapid power line channel variations. Instead, with the low cost associated with estimating the echo channel digitally, IBFD devices may afford to use algorithms like recursive least square (RLS) adaptation or variable step-size LMS algorithms for improved convergence. Alternatively, a suitable PLC-specific echo channel estimation is the LPTV-LMS algorithm, which exploits the linearly periodic time variations (LPTV) observed in power line channel conditions to provide improved convergence without any increase in computational complexity [4].

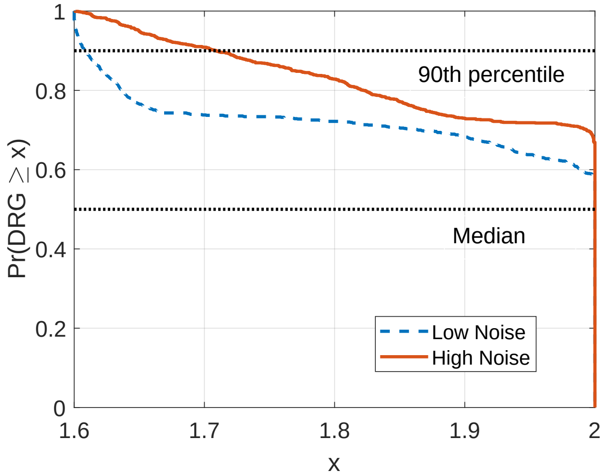


Fig. 3. Tail distribution of DRG achieved using D-AIC solution for BB-PLC obtained over a set of 1500 random in-home power line channel and noise conditions. The run-to-run channel condition was varied by randomly choosing different network loads connected to the 15 outlets associated with each of the 15 derivation/junction boxes in the indoor electrical wiring. At every run a random power line noise signal was also added. The parameters associated with the noise model were varied between its possible extremes to generate the low and high noise conditions.

C. *IBFD-PLC Performance*

Due to the rapid channel variations, IBFD solutions for PLC are expected to operate continually without requiring any start-up or silent periods during operation. As a consequence, the echo estimation algorithm functions in the presence of the SOI, using the composite received signal consisting of the SI, SOI, and noise, as the reference signal. Hence, the accuracy of the echo estimate is dependent on the relative power of the SOI, which is driven by the power line channel attenuation it experiences. A weak SOI resulting from a high PLC channel attenuation enables a more accurate estimate, and therefore leads to greater interference cancellation, and vice versa. Under conditions observed in, say, short PLC links, where channel attenuation is low, the SI reduction algorithm may consequently not perform to its full potential of providing over 80 dB of SI reduction. The simulation result of evaluating data rate gain (DRG), which is defined as the ratio of the bidirectional data rates under IBFD to HD mode, for D-AIC in an IBFD BB-PLC device is shown in Fig. 3. The tail distribution of DRG shows that although D-AIC counters the impact of quantization noise, operating in presence of SOI, which can occasionally be relatively strong due to low channel attenuation, hurts the achievable interference cancellation. As a result, doubling the data rates is accomplished in about 60-70% of the tested network conditions. We also notice that under high power line noise scenarios, we obtain a higher DRG when compared to a low noise environment, since it requires lower SI reduction to close the gap between SSINR and SNR in IBFD and HD modes, respectively.

III. IBFD+: BEYOND DOUBLING DATA RATES

As indicated in the introduction, IBFD operation provides benefits to communication networks beyond doubling physical layer transfer rates. Most of these benefits, such as enhanced relaying, IBFD jamming, and handshake-free hidden node resolution, are universal in nature and have been widely investigated in different communication systems, including PLC [2], [10]. In this section, we highlight PLC-specific issues where the IBFD operation allows for the design of efficient solutions, some of which were long been considered to be infeasible in PLC.

A. *Enhanced PLC MAC Protocols*

Among the various application scenarios, PLC finds widespread applicability in in-home networks for multimedia communications and home automation. Such networks are often characterized by a large number of connected devices, which are increasing by the day with the expansion of the Internet-of-Things (IoT). However, contemporary PLC network performance deteriorates, especially at the medium access control (MAC) layer, with increasing number of connected nodes. This MAC layer performance degradation hinders the translation of advancements in the physical layer technologies on to improvements at the higher layers. Two major reasons for the reduction in MAC efficiency, which can be defined as the ratio of the time spent in transmitting data payload to the total time spent on all activities at the MAC layer, are due to the overhead times involved in resolving contentions and recovering from collisions. In this context, the IBFD operation can be used to design solutions that can counter both these issues.

Most PLC MAC protocols support carrier sense multiple access with collision avoidance (CSMA/CA) as the primary multi-user channel access protocol together with a binary exponential random backoff procedure [1, Chs. 8, 9] to reduce packet collisions. However, when a packet collision eventually occurs, the probability of which grows with increasing number of participants, recovering from collisions under the conventional HD operation consumes an extended duration of time [11]. On the other hand, by allowing simultaneous transmission and reception, IBFD allows the PLC nodes to transmit data packets and sense their status at the same time. Therefore, any packet collisions are instantaneously detected by all the IBFD nodes involved in transmission, and the recovery procedure can be immediately initiated to accomplish a CSMA-with-collision-detection (CSMA/CD) protocol.

The second time consuming period during which no data is transmitted is while resolving contentions, which could be lengthier than the duration of the data payload itself. Toward efficient contention resolution, the legacy time-domain backoff procedure can be replaced with a frequency-domain contention resolution, where all the participating network nodes advertise their chosen random backoff counter (BC) value at the same time on orthogonal sub-carriers. Using IBFD operation, every participating node can then not only learn the BC values of every other node with minimal spectral leakage to cooperatively pick the one with the smallest BC as the winner, but can also detect if there are more than one nodes with the smallest BC to thereby predict a future collision. In this manner, an enhanced frequency domain contention resolution with integrated CSMA/CD operation can be realized [12, Ch. 4.4].

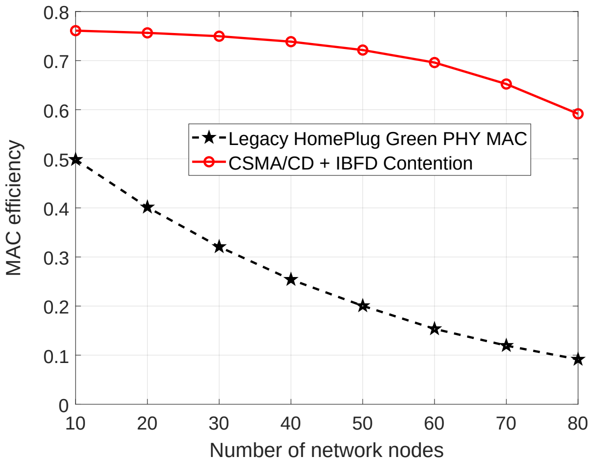


Fig. 4. Variation of MAC efficiency with the number of participating network nodes using the legacy MAC protocol and the improvement with IBFD operation. The simulation evaluation was conducted for an in-home power line mesh network with bi-level priority (lowest or highest) saturated traffic generated by a variable number of nodes. The length of all data frames were set to the maximum frame length stipulated by the HomePlug Green PHY standard. All other simulation parameters, such as inter-frame spacings and frame control and preamble lengths, were also chosen from the HomePlug Green PHY specification.

Simulation results, shown in Fig. 4, for the combined use of both these techniques in lieu of legacy PLC MAC protocol from HomePlug Green PHY standard [1, Ch. 9.2] demonstrates that while the efficiency steadily declines when using the conventional MAC protocol, the IBFD-based solutions of CSMA/CD and frequency domain contention resolution ensure that the MAC efficiency remains fairly constant with a minor reduction only when the network encounters a large number of participants. This multi-fold increase in the MAC efficiency also ensures that the network operation does not collapse under heavily loaded conditions, which is foreseen with the increased applicability of IoT within a smart-home network.

B. *Efficient Handling of PLC Radiation*

The medium-aware transmission ability of IBFD operation that enables CSMA/CD can also be exploited to mitigate the impact of unintentional PLC radiation in both indoor and outdoor applications. Since power lines are electromagnetically unshielded and power line networks are typically unbalanced, the presence of common-mode PLC signal components leads to an increased unintentional electromagnetic radiation.

As an illustration, we focus on BB-PLC, which operates in the frequency range of 2-100 MHz. This spectrum is also

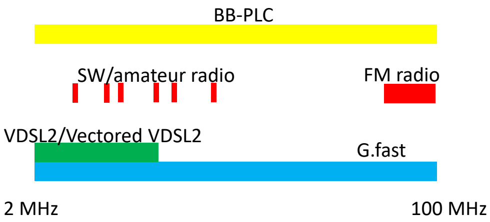


Fig. 5. An illustration of the use of the 2-100 MHz frequency range by BB-PLC, non-PLC wireless services such as short-wave (SW), amateur, and frequency modulation (FM) radio, and non-PLC wire-line DSL communications using the VDSL2, G.fast, or newer standards.

shared by several non-PLC applications, such as broadcast and amateur radio, as seen in Fig. 5. Interference from unintentional BB-PLC radiation onto these non-PLC wireless services is prevented by introducing spectral notches during PLC transmission for the frequency bands used by these non-PLC services. This leads to inefficient spectral usage, since these bands can often be idle. Such *white spaces* can be used for PLC by using a *listen-before-talk* (LBT) approach for transmission. Conventional HD PLC modems that employ the LBT strategy regularly suspend PLC transmission to ensure that the operating frequency band is free. Naturally, this leads to under utilization of the available spectral resources in time. Alternatively, IBFD operation enables the use of a *listen-and-talk* (LAT) approach, since IBFD-PLC modems can now simultaneously transmit data and also sense the spectrum for activity. Such a technique leads to nearly 100% white space usage efficiency, and is shown to provide up to a three-fold data rate increase in the idle bands [12, Ch. 4.1].

Along with wireless radio services, we observe in Fig. 5 that the frequency range of 2-100 MHz is also used by DSL wire-line communications. Since DSL networks are also typically unbalanced, broadband DSL signals cause unintentional electromagnetic radiation while also being susceptible to interference. Prior evaluations have shown that downstream DSL data rates can be improved by up to 80% by mitigating the PLC-to-DSL interference in an in-home environment [12, Ch. 4.2]. Although DSL networks are often the backbone for indoor communications and assume the primary user status in these scenarios, applying spectral notching at the secondary users, that is, at PLC modems, to ensure PLC-DSL coexistence renders PLC largely inoperable, since DSL standards of very-high-data-rate DSL 2 (VDSL2) and newer prescribe the use of a large portion of the 2-100 MHz frequency range and beyond. To this end, the European Telecommunications Standards Institute (ETSI) suggested the use of a dynamic spectral adaptation approach, where PLC modems regularly estimate the DSL-to-PLC channel interference and accordingly adapt the PLC transmit PSD to ensure that the PLC-to-DSL interference is benign [13]. This requires HD PLC modems to regularly suspend PLC transmission to sense the spectrum for interference channel estimation, whereas IBFD operation allows PLC modems to simultaneously transmit PLC data while also estimating the DSL-to-PLC interference to adapt its transmit PSD in real-time.

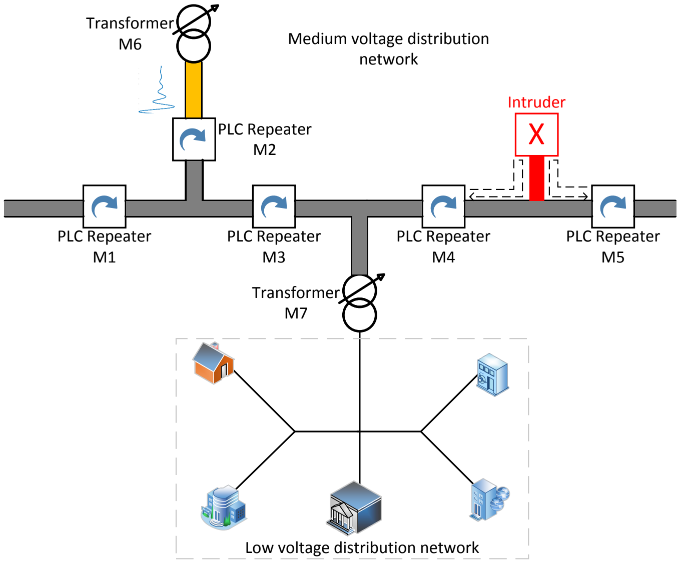


Fig. 6. An example of a smart grid distribution network with communications enabled over power lines, where PLC modems are used as repeaters (M1 – M5) throughout the medium voltage network and are also placed at the transformers (M6, M7). This network has two anomalies: (i) an intruder tapping in between the PLC modems M4 and M5, and (ii) a cable section subject to abnormal degradation between the modems M2 and M6.

C. Smart Grid Security and Asset Monitoring

The echo estimated as a part of the SI cancellation procedure is beneficial on two fronts. Apart from recreating the reflected signal to remove it from the composite received waveform, the echo also contains multipath components of the signal reflected from various impedance mismatches throughout the power line network. Therefore, the estimated SI provides insight into the network topology and conditions of the communication medium and loads connected. A change in any of these entities, therefore, results in a variation in the estimated SI. While many changes are benign and expected, such as varying network load conditions, a change in the estimated SI or the SI channel could also be caused due to, say, a power line segment damage or a possible network intrusion. IBFD-enabled PLC modems therefore provide indications into such possible inconsistencies in network operation [14], [15].

The challenge in monitoring the estimated SI channel to determine network aberrations is in distinguishing corresponding changes in channel condition from those caused due to legitimate network activities. Consider a smart grid distribution network where communications is enabled over the power lines, an example of which is shown in Fig. 6. A passive intruder (INT) who taps into the line to snoop the traveling data is typically hard to detect using intrusion detection methods such as listening for signatures. However, an INT entering the power line network causes an impedance mismatch at its tapping location and thereby leads to a change in the SI estimated by PLC modems in its vicinity. In the network shown in Fig. 6, the entry of an INT between two PLC modems, M4 and M5, causes an additional peak in their estimated SI channels resulting from the extra signal reflection from the impedance mismatch at the location of the INT.

Depending on the power line attenuation, additional reflections could also be observed in the SI channel estimates at modems that are further away. Such subtle changes caused by the INT could be hard to notice manually. However, machine learning based methods can be used to detect such channel variations automatically and also locate the point of intrusion [14].

Further to detecting and locating a network anomaly, the estimated SI channel is also useful to obtain additional insight into the condition. Consider a section of the power line that is subject to irregular degradation, as seen in Fig. 6 between M2 and M6. The damaged section of the line introduces higher attenuation on the signal traveling through it. This can be noticed as a lower-than-usual gain in the estimated SI channel. In this manner, a well-trained machine can assess the health of power lines, which can be used to predict and prevent a future in-service failure. This principle of monitoring the estimated SI channel can be used either as a stand-alone solution or as a complementary method to existing techniques to continuously monitor various grid assets [15].

IV. CONCLUSIONS

Although IBFD operation has long been used in various communication systems, its application in PLC presents unique challenges. This article highlights the design considerations for IBFD-PLC, including the PLC-specific challenges faced and the beneficial features that simplify an IBFD solution. Along with networking benefits that full-duplex operation provides for any communication system, it also solves electromagnetic interference issues and provides insights into the power line network components, which are unique to PLC. In light of all the recent advancements, IBFD for PLC is being considered to be incorporated in the upcoming G.hn2 standard for unified wire-line communications for home networking.

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